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PROPORTIONAL NAVIGATION WITH ADAPTIVE TERMINAL GUIDANCE FOR AIRCRAFT RENDEZVOUS (PREPRINT)

Austin L. Smith

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AIR VEHICLES DIRECTORATE
AIR FORCE MATERIEL COMMAND
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542

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14. ABSTRACT

- PN with adaptive terminal guidance is shown to be a viable guidance method for aircraft rendezvous in 6DOF simulation.
- Adaptive PN and Velocity controller combination is shown to effect successful rendezvous.
- Adaptation accounts for errors caused by assumptions (stationary RZ location), wind, and tanker maneuvers.

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Proportional Navigation with Adaptive Terminal Guidance for Aircraft Rendezvous

Austin Smith

Austin.Smith@wpafb.af.mil

Background

- Automated Aerial Refueling (AAR) requires receiver-to-tanker rendezvous
- A trajectory/guidance algorithm is necessary to provide a path/FCS commands for the aircraft rendezvous
  - Optimization algorithms are computationally intensive
  - Geometric solutions limit UAV maneuvering
  - Trajectory solutions may “jump” around

Current CONOPS for AAR is the trajectory algorithm brings the UAV to a 1-NM trail position, where a tanker relative control law is engaged

Very difficult to embed an iterative optimization algorithm in a FCS running at high rates

Geometric solutions (even when iterative) may not control speed or provide a smooth rendezvous (zero turn rate at RZ)

Useful to look at a simple algorithm that meets rendezvous contraints (same V, Psi, Pos at same time) that can be embedded in a FCS

Requirements

- Able to embed into UAV FCS and run real-time
- Use same information as FCS (AAR PGPS)
- Must obey vehicle limits, and tactical and operational CONOPS
- Execute successful rendezvous

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Must be able to embed guidance algorithm into FCS running at high rate

Must use same information as inner/outer loop, Precision Differential GPS

Proposed Guidance System

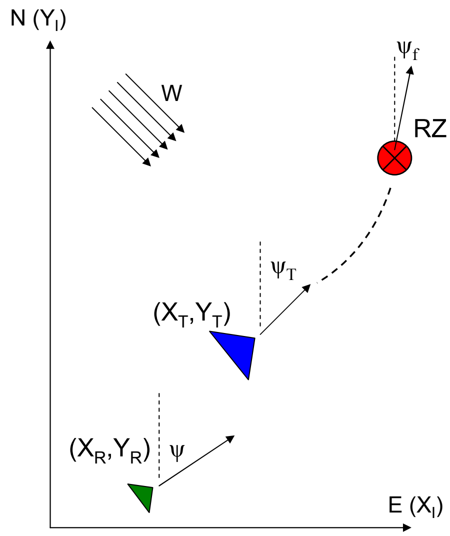
- A proportional navigation guidance system with adaptive terminal guidance,

  And a velocity control loop that…
  - Commands UAV to RZ location with the same speed and heading as tanker, at same time
  - Obeys velocity, acceleration, and turn rate limits
  - Is robust to winds and tanker maneuvering

Design Approach

Design

- Treat target as stationary, using an adaptive “tanker estimator”, based on kinematics, to determine a rendezvous (RZ) location
- RZ location approaches tanker as receiver’s heading and position approach tanker’s heading and position
- Velocity loop will control speed
- 2-D (constant altitude)



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Use “estimator” to determine a target location, prevent prolonged “tail chases”

Wind component

The adaptive terminal guidance pronav will provide a turn rate command to align UAV heading with tanker heading at or before rendezvous location

Two main coordinate systems, flat earth N-E and RFE (tanker relative)

Tanker estimator depends on turn rate of tanker for locating a rendezvous point based on tanker states and UAV states

Guidance Law
Proportional Navigation

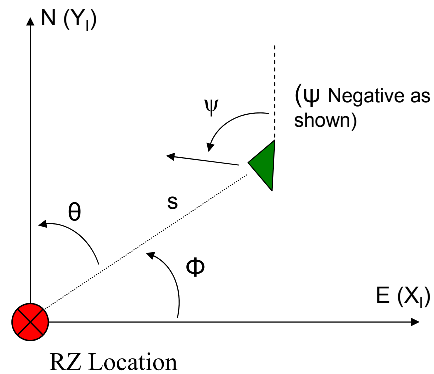
$$\dot{\psi}_{com} = -\lambda_1 \dot{\phi} \quad \text{where} \quad \dot{\phi} = \frac{d(\Phi_f - \theta)}{dt} = \frac{(\dot{y}_R - \dot{y}_T)(x_R - x_T) - (\dot{x}_R - \dot{x}_T)(y_R - y_T)}{s^2}$$

and

$$s = \sqrt{(X_{I,R} - X_{I,T})^2 + (Y_{I,R} - Y_{I,T})^2}$$

assuming

$$\dot{x}_T = 0, \quad \dot{y}_T = 0$$



Variation of control law from Lu, Doman, Schierman

Note different definitions for heading and LOS orientation

S is range-to-go

Phi final is a function of final heading constraint

Guidance Law
Adaptive Update

Initially…

$$\lambda_1 = \frac{-(\Psi_f - \psi)}{(\Phi_f - \phi)} \quad \text{or} \quad \dot{\psi}_{com} = \dot{\psi}_{\max}\,\mathrm{sgn}(\Phi_f - \phi)$$

$$\left.\begin{array}{l} \lambda_1 > 1 \Rightarrow s \to 0 \\ \lambda_1 > 2 \Rightarrow \Phi_f = -\frac{\pi}{2} - \Psi_f \end{array}\right\} \text{Guidance Law Properties}$$

Adaptation…

$$\dot{\lambda}_1 = -\frac{\kappa}{s^2}\left(\lambda_1 + \frac{\Delta\psi}{\Delta\phi}\right)\left((x_R - x_T)(\dot{x}_R - \dot{x}_T) + (y_R - y_T)(\dot{y}_R - \dot{y}_T)\right)$$

where… $$\begin{cases} \Delta\psi = \Psi_f - \psi \\ \Delta\phi = -(\Psi_f + \frac{\pi}{2}) - \phi \\ \kappa = \text{constant gain} \end{cases}$$

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An initial PN gain calc is made, it must be greater than two to guarantee the final heading constraint is met, if it is not >2, then the aforementioned turn rate command is used, which will eventually increase the PN gain above 2

Adaptation ensures final heading constraint is met even when: guidance commands exceed maneuverability of vehicle (alg uses kinematics), limits are saturated, movements in the target caused by tanker drift, winds, etc.

Final LOS angle definition ensures receiver will approach tanker from behind as it nears its final heading

Guidance Law

Velocity Controller

$$A_{com} = -k_1 \frac{\left(V_R - \sqrt{\frac{t_R+1}{t_T+1}}V_T\right)^2}{s} \operatorname{sgn}\left(V_R - \sqrt{\frac{t_R+1}{t_T+1}}V_T\right)$$

$\frac{t_R + 1}{t_T + 1}$ = time-to-target ratio

-Increases or decreases target velocity

-Neither t_R or t_T is a guess of the RZ time or the actual time of arrival to target

-The ratio gives a relative sense of how far ahead or behind the tanker the UAV is from the target RZ location

$(t_R+1)/(t_T+1) \rightarrow 1$ as Receiver and Tanker approach RZ

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Time-to-Target ratio is receiver time-to-target over tanker time-to-target

Less than one, receiver slows down; greater than one, receiver speeds up

Results

- Simulation
  - 6DOF Tanker and UAV models
  - Tanker
    - $\psi_{t=0}=0^{o}$
    - V=670ft/s
  - UAV
    - $V_{t=0}=750$ft/s
  - Wind
- UAV Limits
  - +-2 deg/s turn rate
  - +-2 ft/s^2 accel/decel
  - 600-800 ft/s V range

MATLAB & Simulink

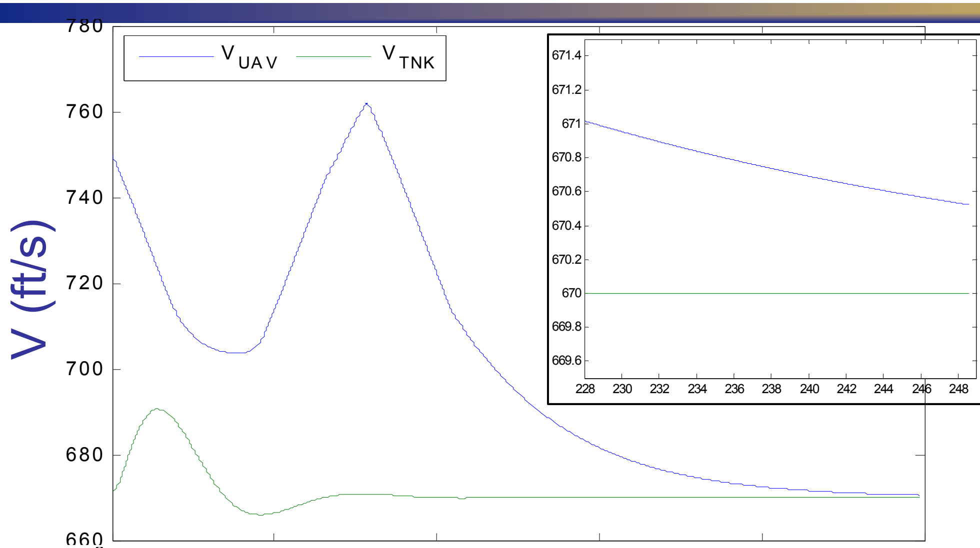
*Everything not listed is variable

Results

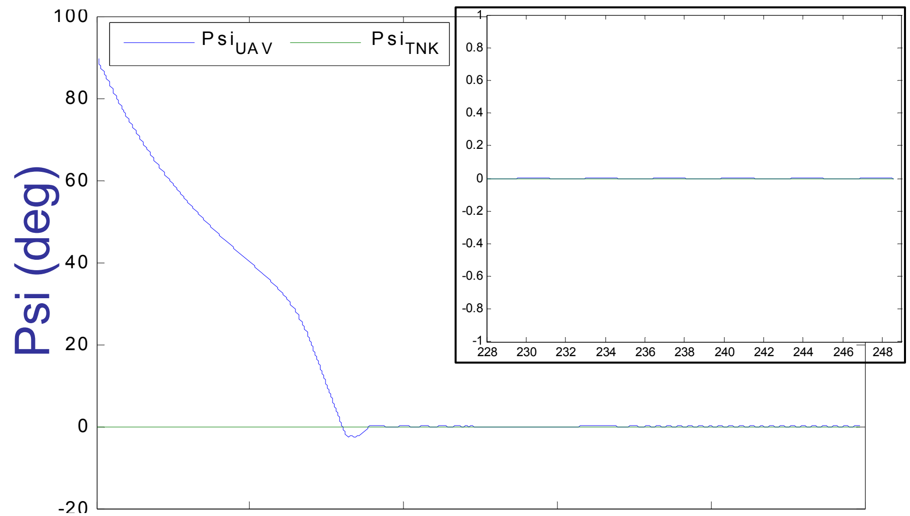
$\Psi_{t=0}$=90º, no wind, $P_{t=0}$=(-40000,15000)ft

-Tanker flying straight leg

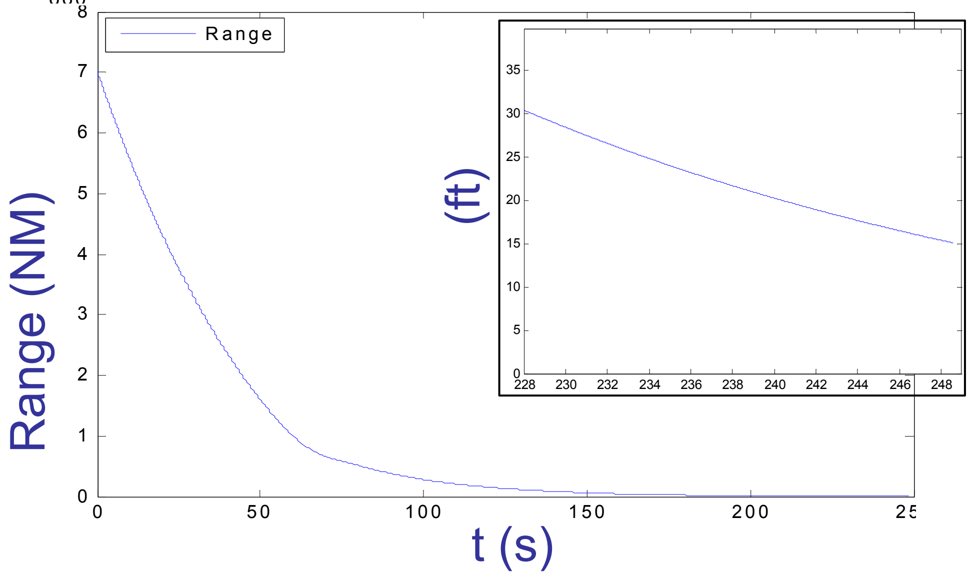
Results



V (ft/s)
V_{UAV}
V_{TNK}
780
760
740
720
700
680
660
671.4
671.2
671
670.8
670.6
670.4
670.2
670
669.8
669.6
228 230 232 234 236 238 240 242 244 246 248



Psi (deg)
Psi_{UAV}
Psi_{TNK}
100
80
60
40
20
0
-20
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
228 230 232 234 236 238 240 242 244 246 248

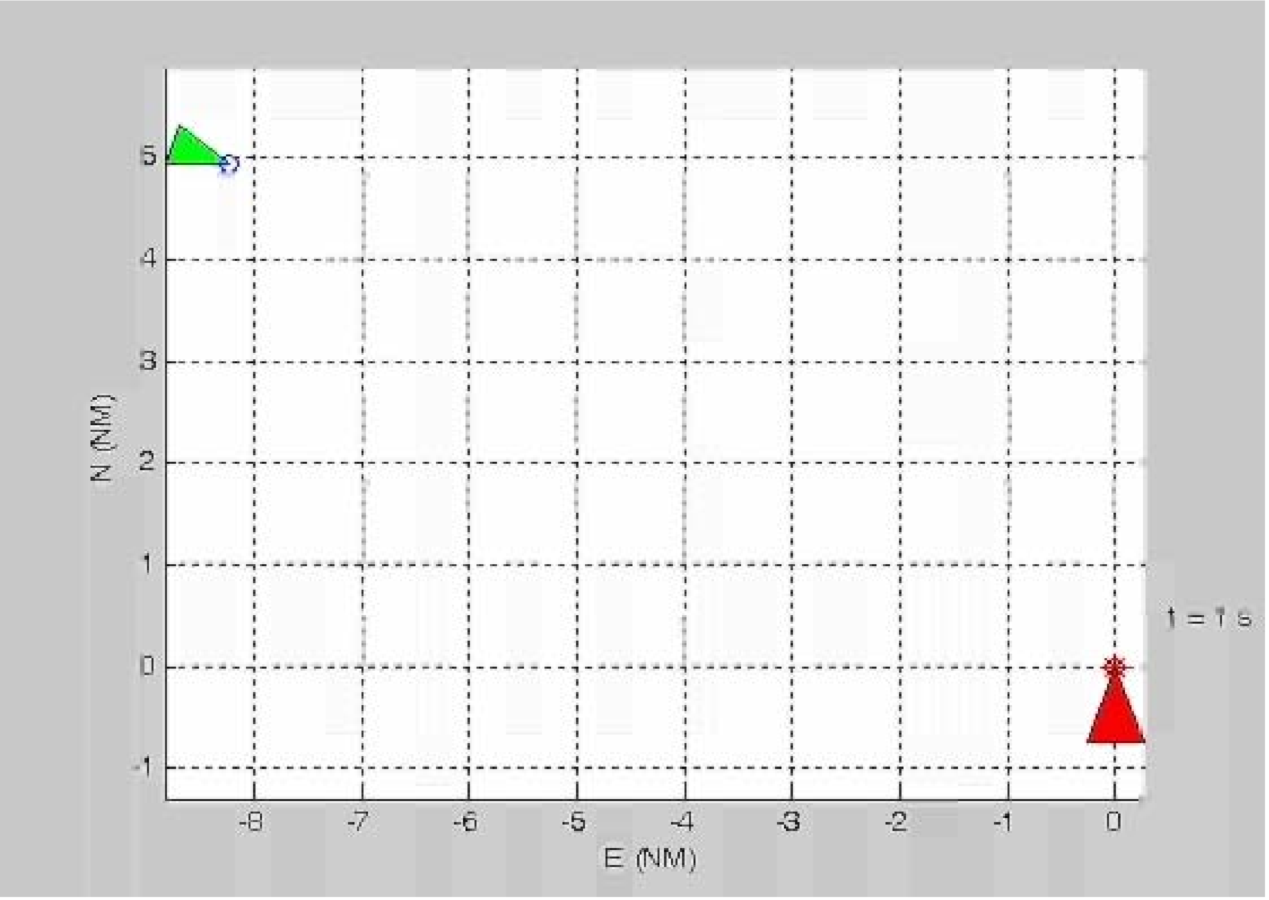


Range (NM)
Range
8
7
6
5
4
3
2
1
0
(ft)
35
30
25
20
15
10
5
0
228 230 232 234 236 238 240 242 244 246 248
0 50 100 150 200 25
t (s)

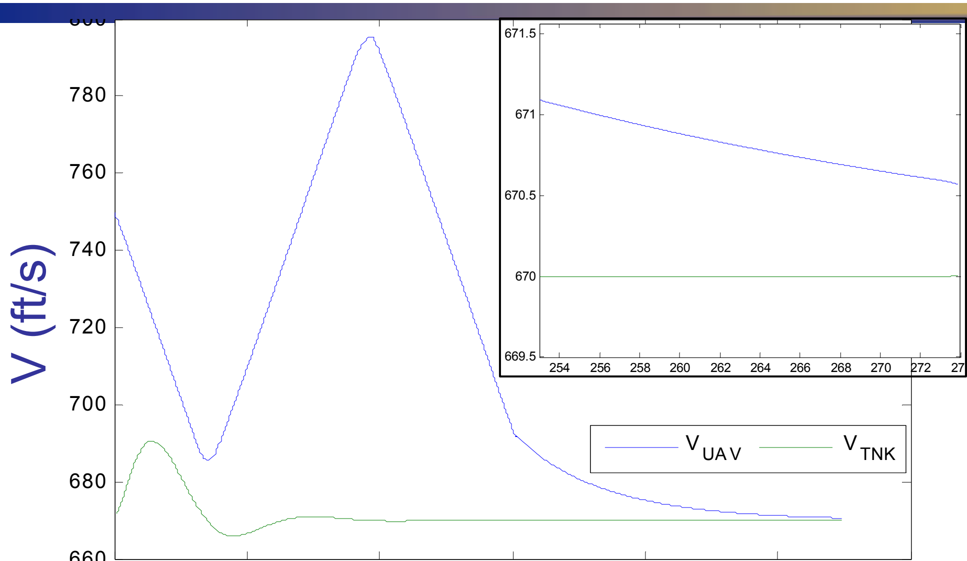
Results

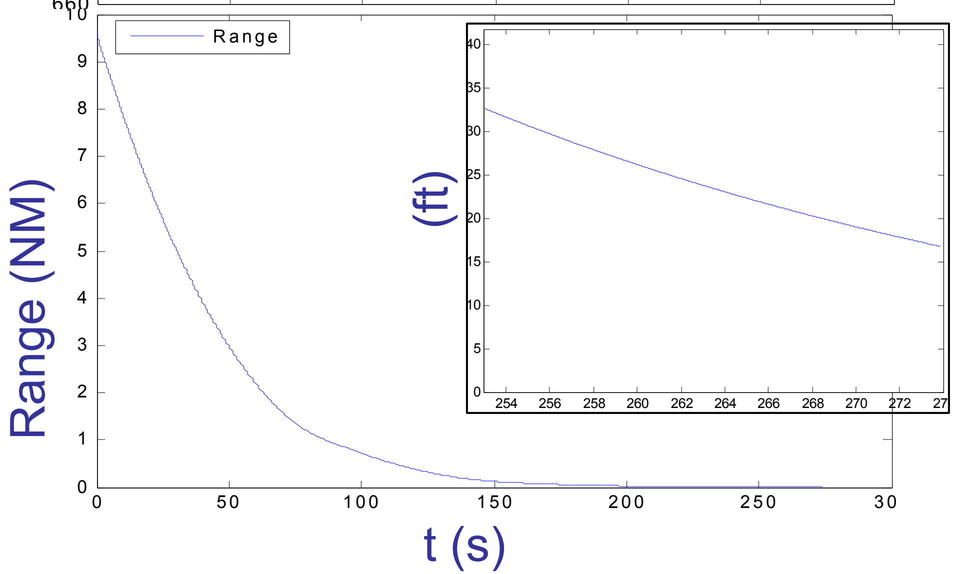
$\Psi_{t=0}$=110º, no wind, $P_{t=0}$=(-50000,30000)ft

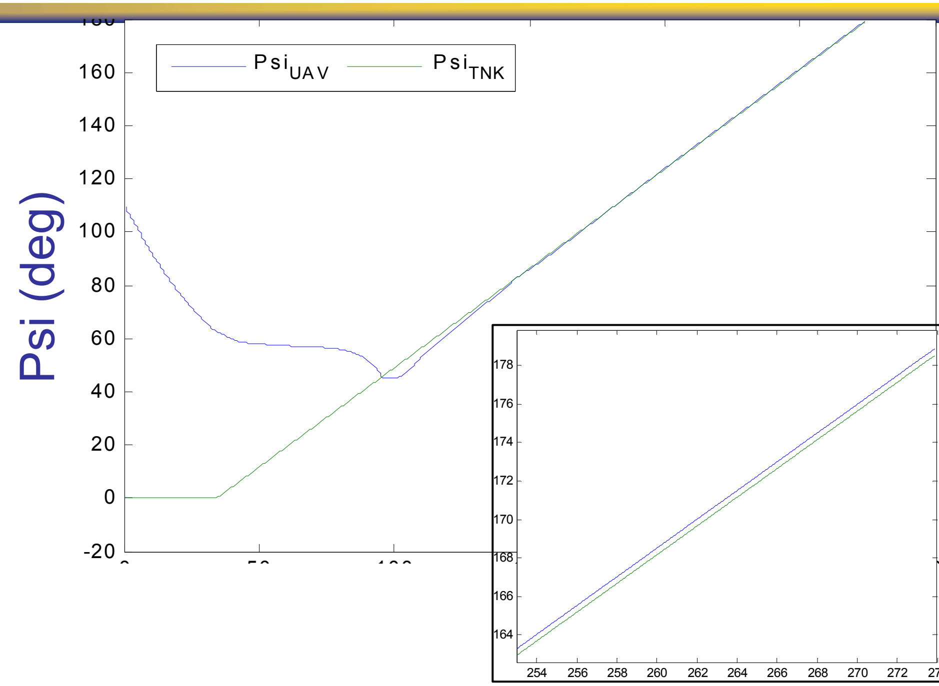
-Tanker turns with 15º bank at t=30s



Results







Turn rate saturated, Receiver crosses tanker path, but comes back around and hits RZ location (but well behind tanker)

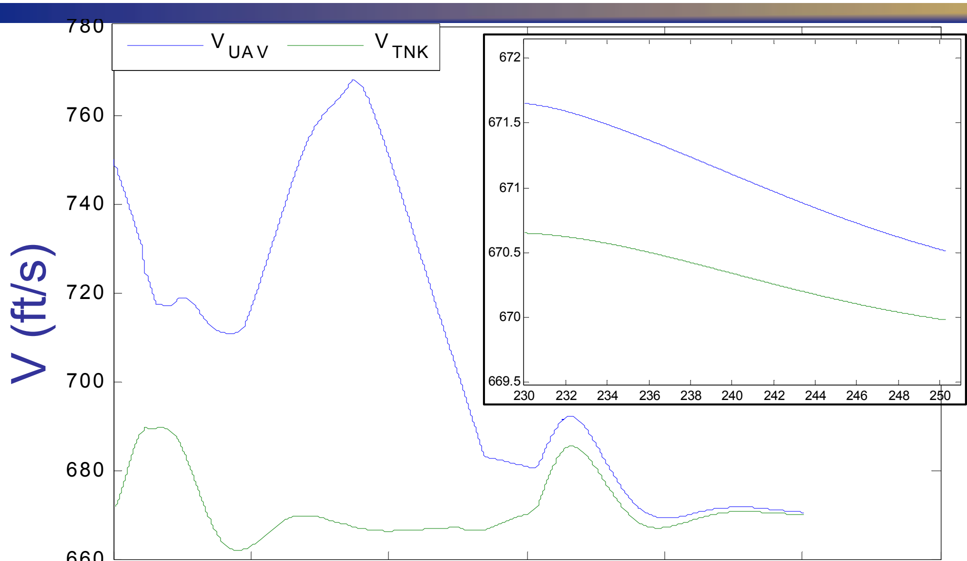
Crossing path behind tanker presents a problem with guidance law because phif - phi -> 0, but RZ is not occurring…logic was introduced to handle this

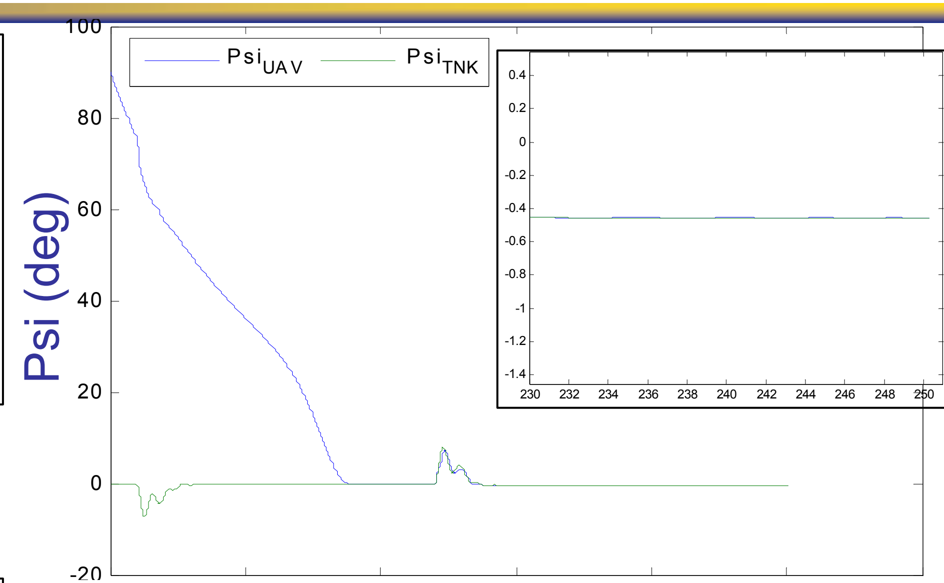
Results

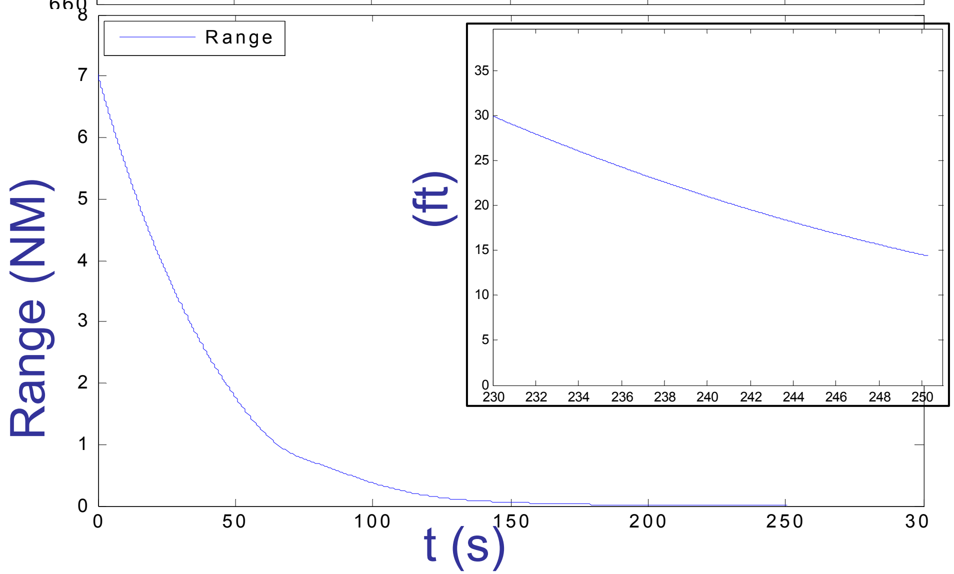
$\Psi_{t=0}$=90º, Wind SE @ 50KT for 100s, $P_{t=0}$=(-40000,15000)ft

-Tanker flying straight leg

Results







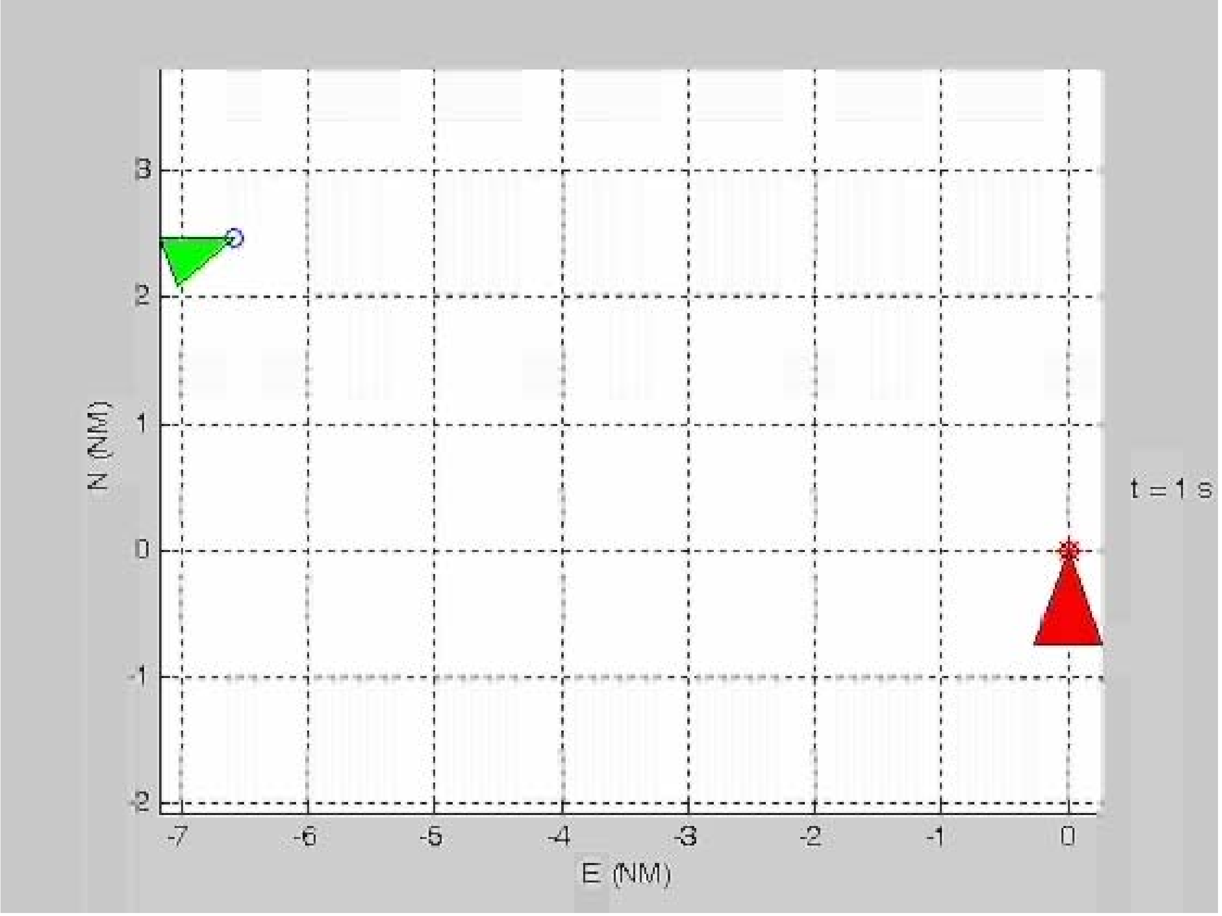
This has both a PN gain re-initialization and winds that test the adaptation

Sequence of target locations reflects tanker maneuver and wind effects

Results

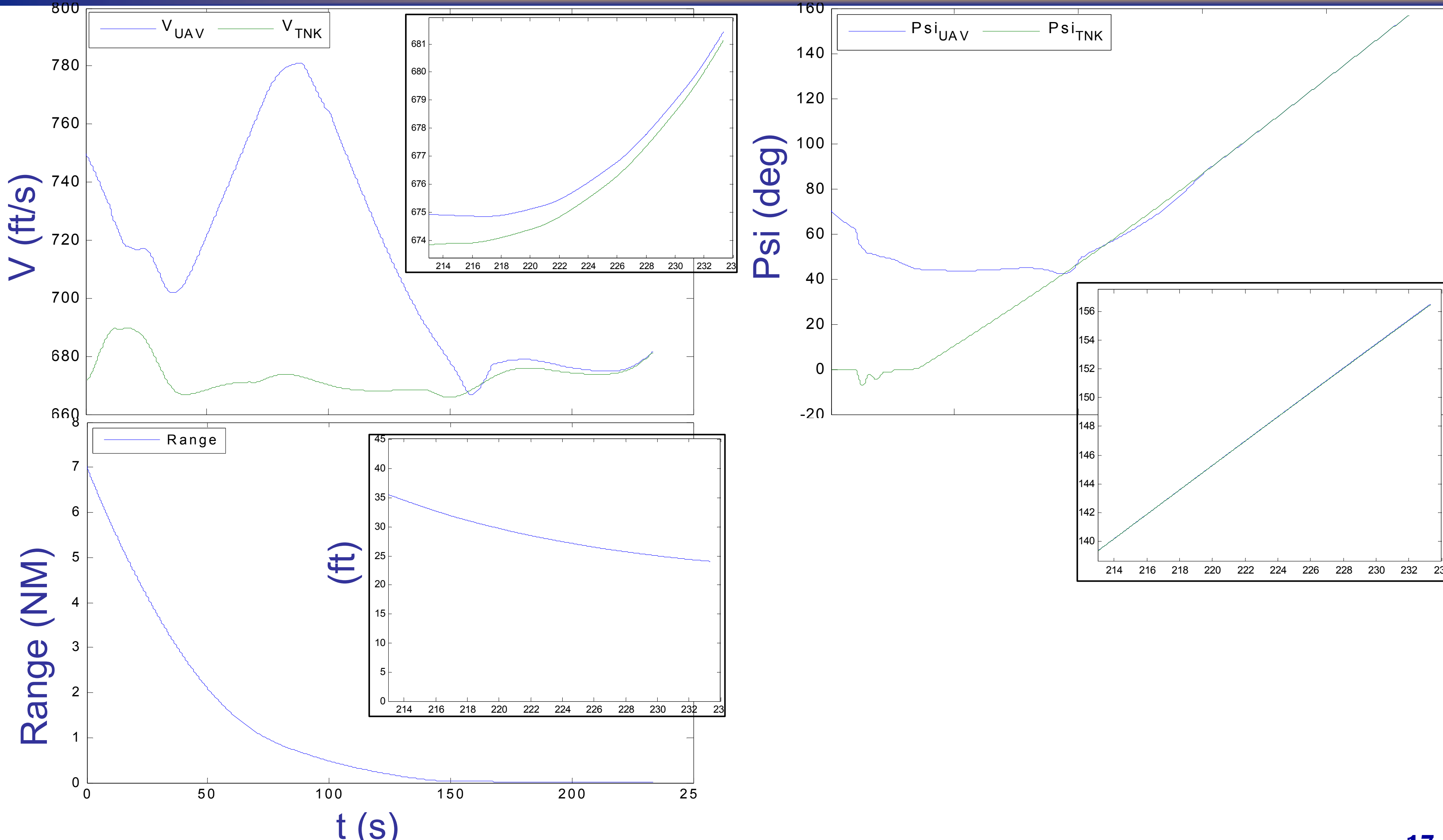
$\Psi_{t=0}$=70º, Wind SE @ 50KT for entire sim, $P_{t=0}$=(-40000,15000)ft

- Tanker turns with 15º bank at t=30s



1st intermediate location based on straight path, when tanker turns, PN gain process restarted for new RZ location on turn

Results



Discussion and Conclusion

- PN with adaptive terminal guidance is shown to be a viable guidance method for aircraft rendezvous in 6DOF simulation
- Adaptive PN and Velocity controller combination is shown to effect successful rendezvous
- Adaptation accounts for errors caused by assumptions (stationary RZ location), wind, and tanker maneuvers

References

[1] Lu, P., Doman, D.P., Schierman, J.D., "Adaptive Terminal Guidance for Hypervelocity Impact in Specified Direction," *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 2, 2006, pp.269-278

[2] Lu, P., "Intercept of Nonmoving Targets at Arbitrary Time-Varying Velocity," *Journal of Guidance, Control, and Dynamics*, Vol. 21, No. 1, 1998, pp.176-178

[3] Ochi, Y., Kominami, T., "Flight Control for Automatic Aerial Refueling via PNG and LOS Angle Control," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Aug. 2005